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E.B. Coy, D.G. Talley, "Progress on Pulsed Detonation Rocket Propulsion at AFRL: Constant-Volume Limit Studies and LOX Spray Detonations" (Abstract)

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(Minneapolis, MN, 10-12 Aug 00) (Submission Deadline: 01 Aug 00)

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PHILIP A. KESSEL Date
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Progress on Pulsed Detonation Rocket Propulsion at AFRL: Constant-Volume Limit Studies and LOX Spray Detonations

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Progress and plans for research at AFRL on pulse detonation rocket engines are described. Analytical studies of the constant-volume limit of pulsed-propulsion have been completed and have shown that the specific impulse penalty of using a fixed area ratio nozzle is less than 3%. Numerical studies of pulsed combustors have elucidated the importance of characteristic times for heat release, chamber blowdown and injector pulsing period. Experimental studies are under way to demonstrate the feasibility of the concept and provide anchoring data for the model. Plans for LOX spray detonation studies are described.

Introduction

The application of pulsed-detonation principles to rocket propulsion presents many unique challenges. For upper-stage and maneuvering engine applications it must be possible to fill and initiate detonation in a vacuum. Oxider, possibly in a liquid and cryogenic state, must be carried requiring the initiation of detonation when both reactants are sprays. A wide range of potential fuels and oxidizers can be considered, with varying kinetic and physical properties. Combustion chamber temperatures will be high which may promote pre-detonations.

In the past, various performance projections have been made showing the theoretical performance advantages of detonative and constant-volume combustion over that of constant pressure. For air-breathing engines, the constant volume limit has been studied, however, it was found difficult to achieve a sufficiently rapid rate of heat release to approach the theoretical performance advantages[1]. Using detonative combustion very high rates of heat release can be realized and this has largely motivated recent interest in this area. When considering the rocket problem, the lack of diluents in the oxidizer stream and the feasibility of using reactive monopropellants suggests that achieving high rates of heat release may not always require a detonation. If this could be shown than the challenges discussed above may not prove to be obstacles for pulsed rocket propulsion.

We envision an engine operating on the following cycle. Propellants are injected in a short burst during the low-pressure portion of the cycle and ignite spontaneously due to the presence of products remaining from the previous cycle. The chamber pressure rises as the combustion products are produced more rapidly than they exit the nozzle and thrust is produced as the propellants expand and accelerate through the nozzle. When the propellants have reacted, the chamber pressure falls and the injection is repeated. Note that this concept does not depend on chamber resonance nor meeting the "Rayleigh condition". This cycle is interesting as a simple analogue to pulsed-detonation as well as a potential alternative in its own right.

Analytical Results

An analytical model of a pulsed propulsion device based on the assumptions of constant-volume combustion of an ideal gas with constant specific heat ratio has been presented by Talley and Coy[2]. The nozzle for this device must be optimized for the entire range of chamber pressures during the blowdown and must accommodate both under-expanded and over-expanded conditions. To establish an upper bound on the performance potential of the constant-volume cycle, fixed expansion ratio nozzles are compared with hypothetical variable area ratio nozzles which are always pressure matched at the exit. Figure 1 gives the results of this theory. The parameter r is the ratio of ~~the final density in the chamber~~ at the end of the blowdown to the initial density and ϕ_0 is the ratio of initial chamber pressure to the ambient pressure. The impulse penalty in using fixed nozzles compared to the variable area case, does not exceed 3% in all cases.

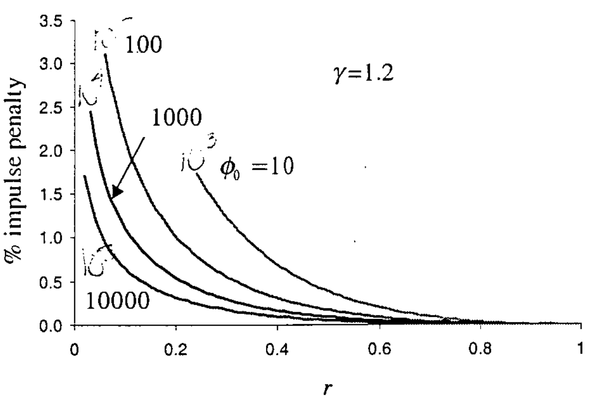

Figure 1. Impulse penalty of an optimized fixed nozzle compared with a pressure-matched variable area ratio nozzle

Comparisons with constant pressure devices were performed which showed that the impulse produced by a constant volume device is superior to that of a constant pressure device when both operate at the same injection fill pressure, but inferior when both operate at the same peak pressure. The magnitude of the difference increases as the ratio of ambient pressure to peak chamber pressure increases and at large values the impulse gain exceeds the performance decrement incurred from a fixed area ratio nozzle. Under vacuum conditions the performance advantage of the constant volume cycle diminishes and may be either slightly higher or lower than the constant pressure device depending on the extent to which the chamber is blown down prior to injection.

Design Calculations

To support the pulse combustor design described below, a numerical model was developed. This is a lumped-parameter code that includes models for the finite rate processes of fuel injection, heat release and blowdown. For the initial proof-of-concept studies, monopropellant mixtures of nitromethane and methanol were studied. The spray is assumed to be comprised of a log-normal distribution of spherical droplets. The surface regression rate is based on a strand burner correlation ~~which~~ that has a nearly linear pressure dependence[3]. Injections occur as discrete events. Continuous injections are divided into a series of individual pulses. The exiting mass flow is assumed to follow the equation for steady flow of an ideal gas through a choked orifice.

Based on the measured characteristics of a fuel injector, the model was used to select a chamber volume and nozzle area that would produce the desired magnitude of chamber pressure oscillations at a specified frequency. In addition to this design work, the model was also used to explore the general characteristics of pulsed combustor behavior.

Figure 2 shows that in the limit of instantaneous injection and energy release the relative chamber pressure oscillations are a function of the ratio of chamber blow down time to the injector pulsing period only. The chamber pressure, P, has been scaled by the steady state chamber pressure, P_{SS}, which is the chamber pressure that would be produced in the same engine geometry operating with at the average mass flow rate. Time has been scaled by the injector pulsing period, t_{PULSE}. Figure 2 can be interpreted as the behavior of chamber pressure when the injection frequency is changed holding average mass flow constant, or by changing the blowdown time of the chamber by changing its volume or throat area while holding injection frequency constant.

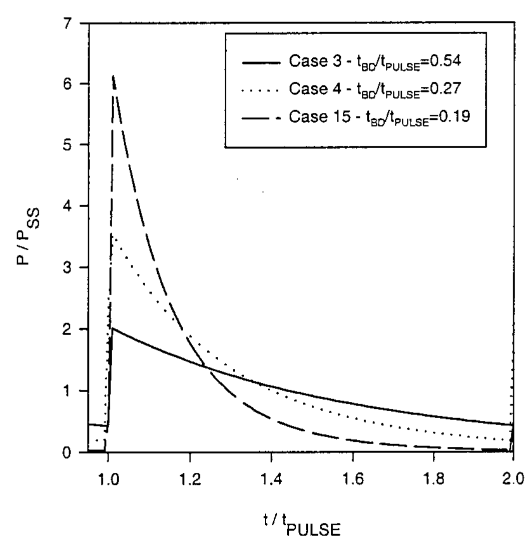

Figure 2. Effect of blowdown time on chamber pressure oscillations in the limit of instantaneous heat release.

Figure 3 shows the effect of finite heat release rate on the chamber pressure oscillations. Case 13 is for a monodisperse distribution of 30 micron droplets and Case 14 is a distribution with a volume average diameter of 30 microns and geometric standard deviation of 2. The effect of finite heat release time is to dampen the magnitude of pressure oscillations while leaving P_{SS}

unchanged. The magnitude of pressure oscillations can always be restored by decreasing t_{BD}/t_{PULSE}.

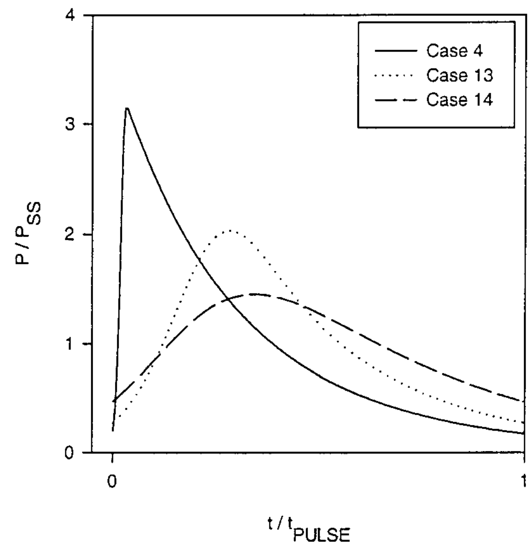

Figure 3. Effect of finite heat release time on chamber pressure.

Experimental Studies

An experimental pulse combustor has been constructed and initial tests are currently under way. The device was designed based on the behavior of a commercially available fuel injector that is used in a gasoline, direct-inject application. A driver circuit was constructed and the device was characterized in our lab and found to be able to operate at frequencies up to 110 Hz while delivering 0.05 ml per pulse at pulse durations less than 2 msec. Based on these values a combustor was fabricated with a volume of 3.5 cm^3 and a nozzle throat area of 2.2 mm^2. This device is predicted to produce peak chamber pressures of 12 MPa and minimum pressures of 0.34 MPa, while operating at 100 Hz. The monopropellant is ignited with an initial flame of hydrogen and oxygen which is turned off after ignition. The chamber and injector are instrumented with strain gage and piezoelectric pressure transducers to characterize the heat release rates of the monopropellant as well as to provide anchoring data for the design code discussed above.

LOX Spray Detonations

Although detonations have been studied extensively, there have been almost no applications in rocket propulsion systems. Studies of condensed phase and heterogeneous detonations have focused on problems related to explosives such as detonations in liquids and solids with low fractions of porosity. It is unlikely that this information will be directly applicable to PDRE's. There is a lack of information for the density ranges and propellant combinations likely to be of interest. LOX is frequently proposed as a likely choice for a PDRE propellant, however, there have been no studies of detonations in LOX sprays that are available to the PDRE community.

In detonations of low vapor pressure sprays, the breakup of droplets dominates the structure of the detonation, and the reaction zone is much longer than for gaseous fuels. Although the basic physical mechanisms involved have been described, it is not yet clear whether other mechanisms might also be important. Even if the above mechanisms are sufficient, a great deal of work remains in quantifying the detonation limits and rate controlling processes.

We are currently preparing a laboratory for studies of detonations of liquid oxygen sprays. The initial focus will be on the high performance liquid oxygen/gaseous hydrogen combination. The use of gaseous hydrogen will allow low liquid fraction systems to be studied first, which will have relatively lower peak pressures. Higher liquid fraction systems will then be explored using gaseous hydrocarbon fuels. Based on the results of these tests, it will be determined if a study of liquid hydrocarbon/liquid oxygen combinations is warranted. Cryogenic liquid methane may be of particular interest as it is completely miscible with liquid oxygen.

Detonation tubes appropriate to the propellant combinations will be fabricated. Each will provide flexibility with respect to mixture preparation and initiation methods, and will be extensively instrumented for mixture and detonation characterization. The devices will be used to study the effects of droplet shattering, atomization, partial vaporization, and thermodynamic state. Of particular interest will be measurements of the pressures generated at the closed end of the tube behind the detonation as these are the primary contributor to the thrust generated by a PDRE.

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[1]Zipkin, M.A., Lewis, G.W., "Analytical and Experimental Performance of an Explosion-Cycle Combustion Chamber for a Jet-Propulsion Engine," NACA TN 1702, 1948

[2]Talley, D.G., Coy, E.B., "The Constant Volume Limit of Pulsed Propulsion for a Constant γ Ideal Gas," AIAA 2000-3216

[3] Lu, Y.C., Boyer, E., Kock, D., Kuo, K.K., "Measurement of Intrinsic Burning Rate of Nitromethane," AIAA-3107, 1997